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Development of High Performance Laminated Electroformed Shape Memory Composite Materials for Lightweight and Deployable Optics

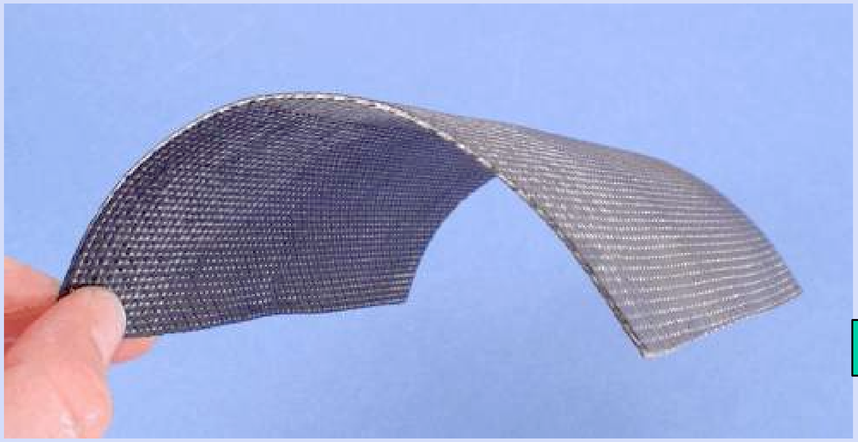
ACT-02-0096

Contract NAS1-03007

The Best of Two Worlds

Nickel electroformed replica:
Smooth, accurate optical surfaces

Shape memory polymer- carbon fiber reinforced, for light weight and controllable deployment



Deployable, lightweight optics

ESSP Needs for Deployable Optics

- **ESTO Workshop (2003) identified multiple mission needs for deployable imaging systems requiring apertures of 1 to 5 meters and larger**
  - Microwave- soil moisture, temp radiometry, cloud heights
  - IR- temperature measurement, radiometry
  - SAR
  - Visible- Lasercom, LIDAR

- **Deployable optics are an enabling technology for many missions**
  - Lighter weight and stiffer optics
  - Instrument capabilities enhanced at larger apertures
  - Cross enterprise value to OSS, Exploration missions

Why Consider Shape Memory Composite Optics?

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- **Large optics fold in a small package**
- **Replication – Cost and time savings**
- **Larger design parameter space**
- **Adaptable to in-space deployment and active control**

- **Study goals :**
  - Shape control with smooth surface (2 nm RMS), low mass (1-5 kg/m^2)
  - Replication accuracy ($<10\lambda$)
  - Stability (temperature, vacuum, creep)
  - Deployability and repeatability ($1:10^4$)

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Concepts unique to replicated shape memory/plating laminate

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- **Surface Replication: low stress nickel**
  - Replicates optical figure
  - Good surface finish
  - Tough, flexible, Established processes
- **Shape memory resin composite**
  - High stiffness, low mass
  - Suitable for Replication Processes
  - Low outgassing
  - Deployable
- **Manage the interface stress between the composite and nickel for shape control**

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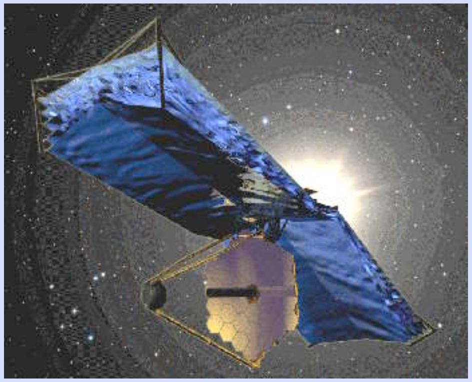
Team Responsibilities

- **Ball Aerospace**
  - Concept development and evaluation
  - Integrated Modeling
  - Application engineering



- **Cornerstone Research Group**
  - Specialized shape memory polymer tailoring
  - Composite reinforcement schemes
  - Fabrication of composites

- **Northwestern University**
  - Electroplated optics fabrication
  - Materials research expertise

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Combining skills and processes

- Modeling of the composite structure and nickel
- Electroplating processes
- Composite resin and structure development

Modeling Summary

- Comparison of model results and experimental results show promise for using the model to help define hardware parameters
- Current simplified model will be translated into more detailed FEM and thermal models
- These models can be easily added to an integrated end-to-end model being developed under other applications

Model Goals and Assumptions

- **Development of material performance models for design**
  - Modeling based on measured material properties
  - Provide information for future sample preparation
  - Characterization and definition of properties/processes/geometry to characterize or control
- **Continue to update design models using measured performance data and define parameters necessary for optimizing and scaling-up the process to larger optics**

- **Current model is simple, Excel based**
- **Can be used to "engineer" the needed materials and structures**
  - Preferential shaping, balancing thickness and properties
- **Incorporates thermal, material and structural properties**
  - Input parameters defined by test results
- **Includes flat and single curved mirrors**
- **Each material layer is homogeneous**

Preliminary Results of Model

- **Model run for Styrene SMP with 3D Weave Carbon**

- **Deflections ("roll-up") of convex samples within 50% of experimental data**
  - Due to temperature change (110 C in oven)
  - Due to added forces
  - Formula used for flat samples to be modified for better accuracy on curved samples

- **Change in length of flat samples due to temperature change within 20% of experimental data**

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Detailed Modeling

- **Update for new material constructions**
  - Symmetric laminations for stability and uniformity
- **Comparison with strain measurements made on samples**
  - New constructions fabricated and entering test
- **Scalability**
  - Utilize scaling methods developed for other large space structures

- **Translate current model into more detailed Finite Element and thermal models that are linked**
  - Include double convex design
  - Include other materials in the lamination
  - These models can eventually be integrated into a formal Integrated End-to End Modeling (IM) environment
- **IM can include theoretical models for items such as the effect of material microyield on the mirror**

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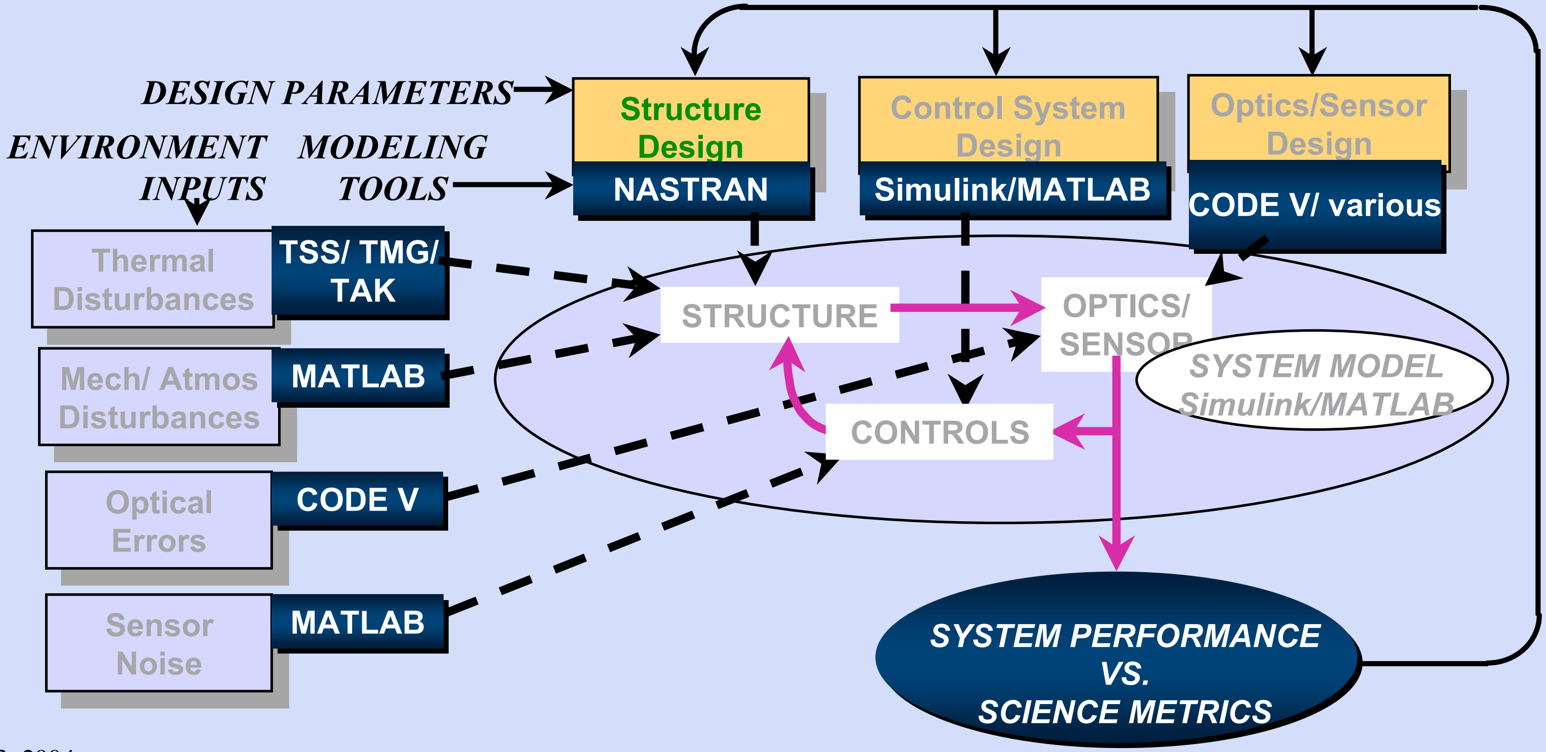
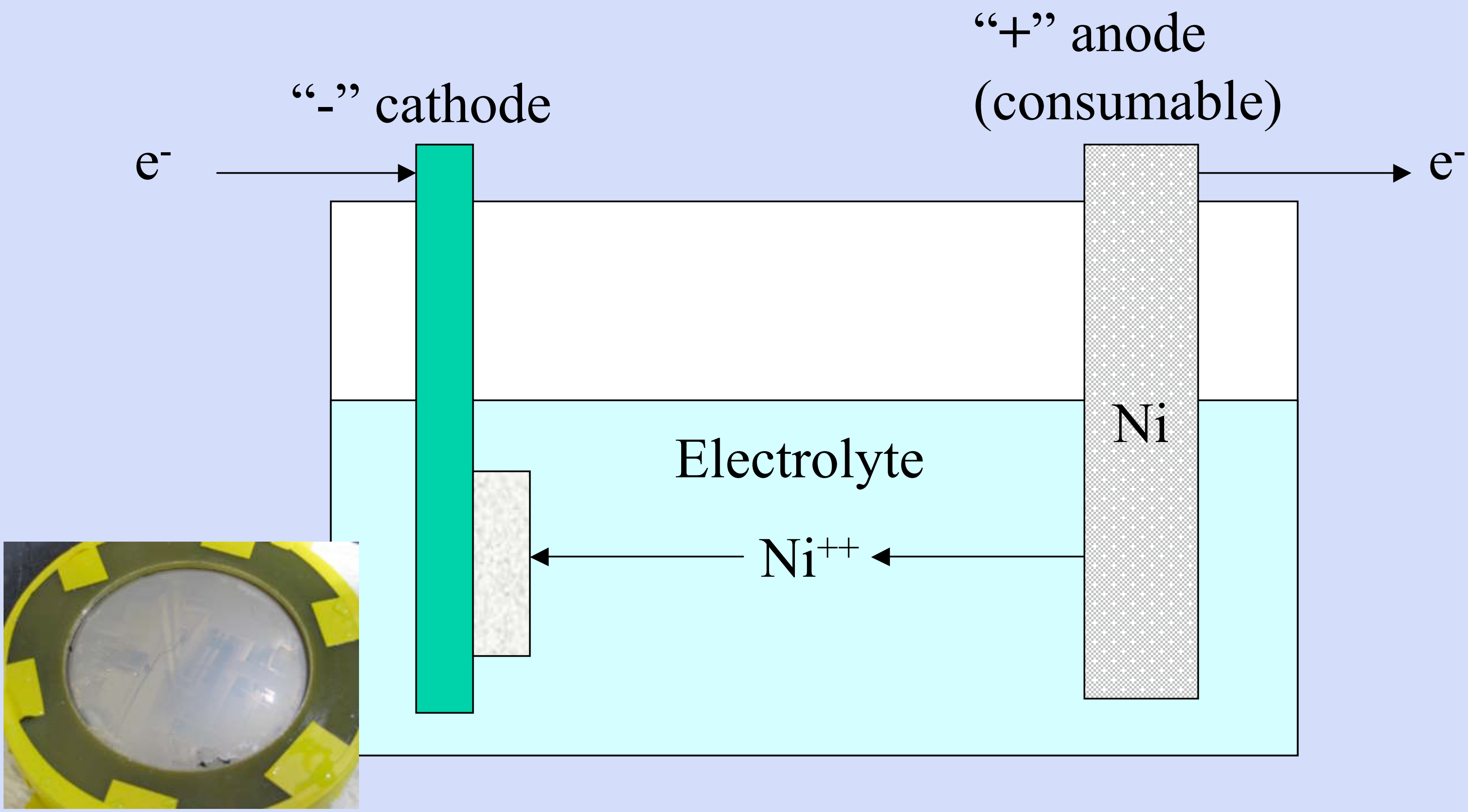
Ball Integrated End-to-End Modeling Environment

- Unique Ball capability under development for 7 years.
- State of the art integration capability for coupled /optical /structural /controls /sensors / signal processing/ and disturbance models - no artificial boundaries between disciplines.
- Simulink / MATLAB based environment - cradle to grave system engineering tool
- Note that experts retain traditional role.



Low Stress Electroplating



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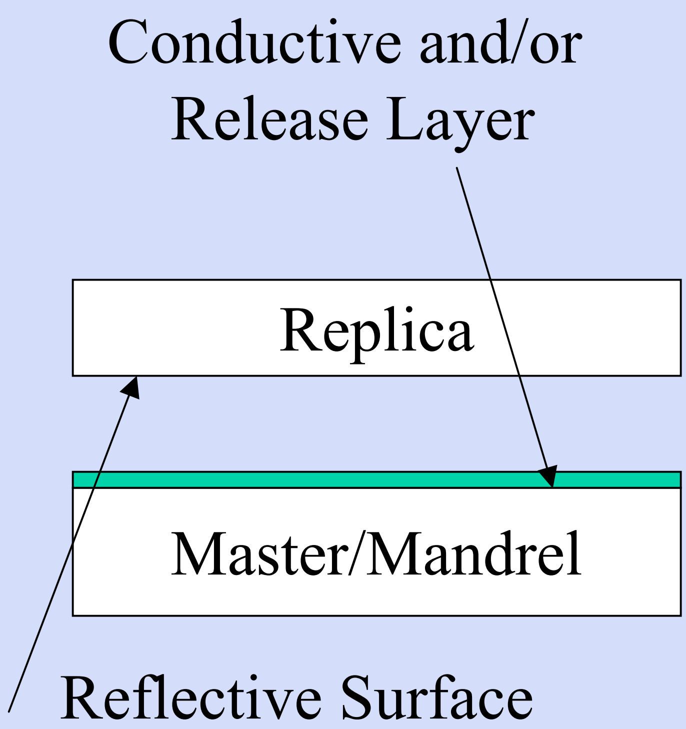
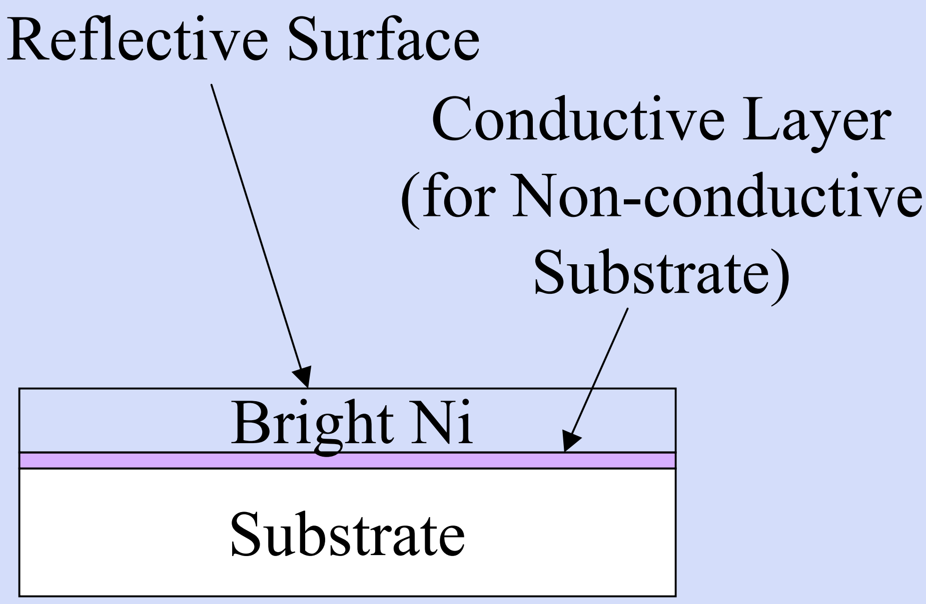
Two Approaches for Mirror Fabrication

Electrofabrication (replication)



Electroplating



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Superpolish Surface Replicated in Nickel

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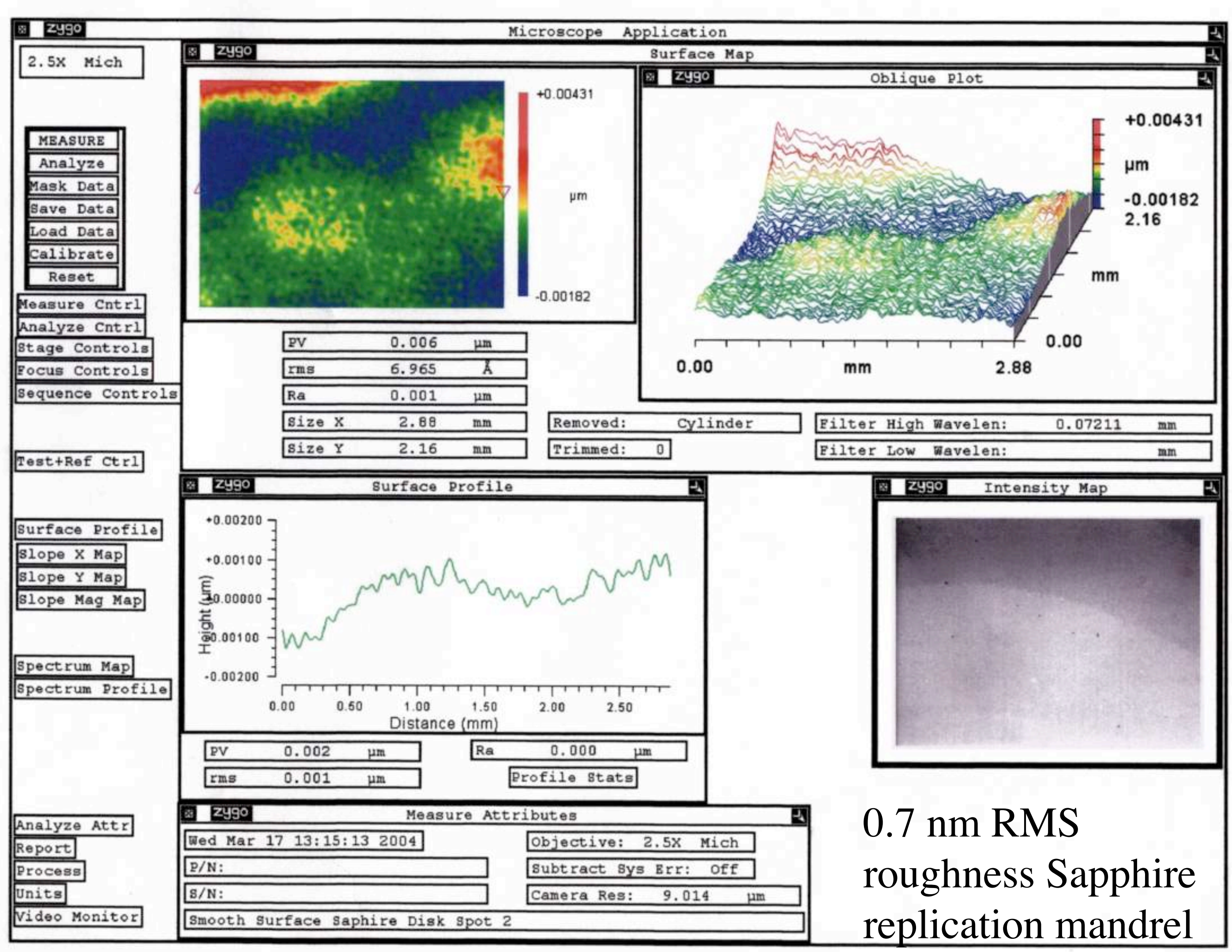

0.7 nm RMS roughness Sapphire replication mandrel

Surface roughness data meets 2nm RMS

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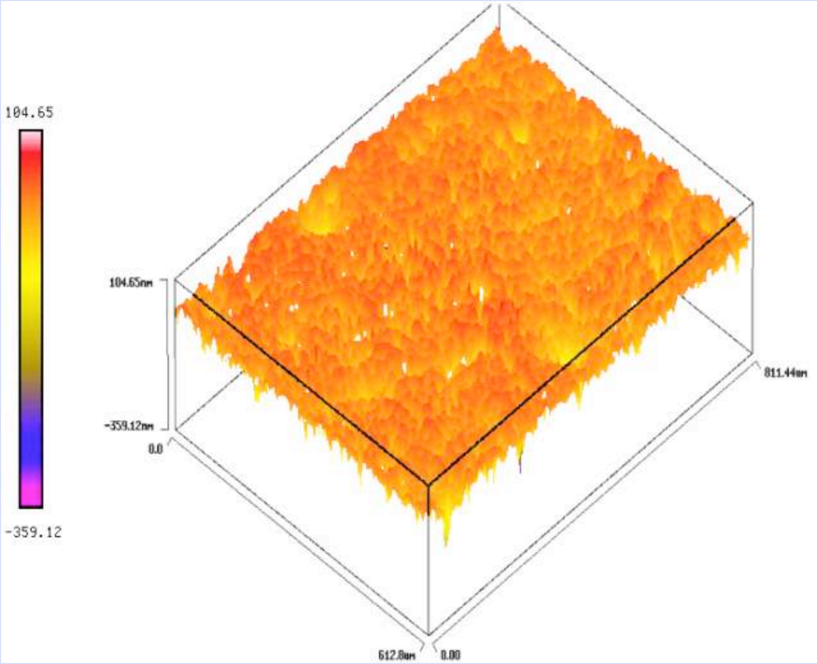

- Zygo interferometer scan data from a developmental cyanate ester resin cast sample.
- Sample shows resin itself meets 7nm roughness, and is unlikely to distort nickel

- Zygo interferometer scan data shows nickel can meet at least 2 nm roughness
- 0.7 nm polish sapphire flats coated to demonstrate maximum replication smoothness

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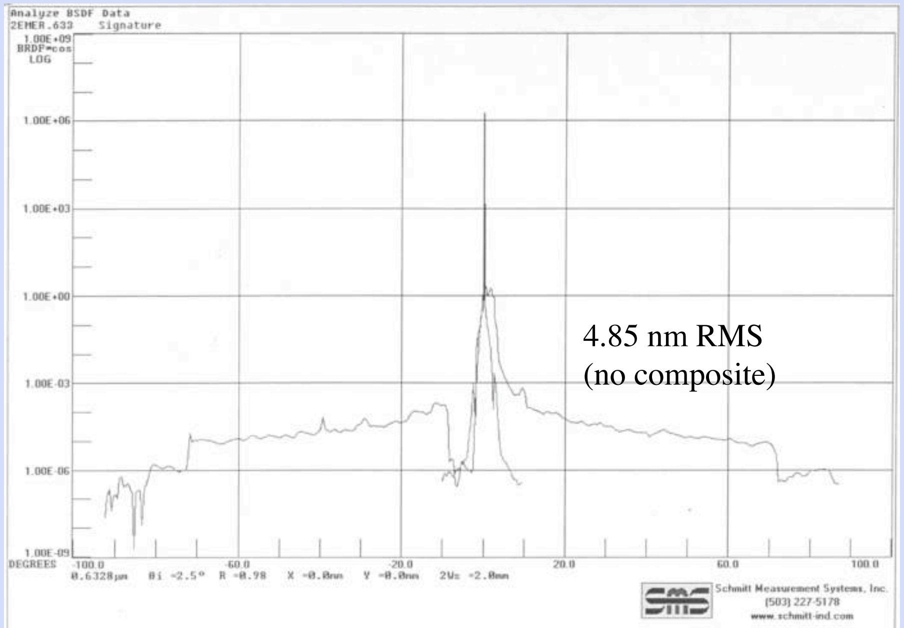
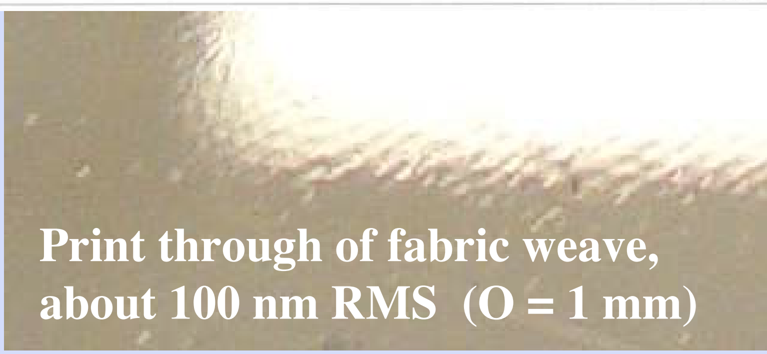
Surface scatter replication dominated by print through





Print through of fabric weave, about 100 nm RMS (O = 1 mm)

- **4.85 nm RMS surface roughness replicated in 20 micron thick nickel from polished flat (no composite backing)**
- **After laminating composite to the back of 20 micron nickel, print-through results in high apparent roughness, profilometer indicates 3 microinch (100 nm) roughness about ~ 33 nm RMS measured with scatterometer**
- **New composite replication process has demonstrated <5 nm RMS roughness, to be tested with high smoothness (0.3nm) nickel replication mandrel**

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Shape Memory Polymers
Application

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- **Actuation**
  - Store and release mechanical energy
- **Reconfiguration**
  - Temporary modulus reduction to enable shape change
- **Replication**
  - Replicate surface from master in manufacturing processes

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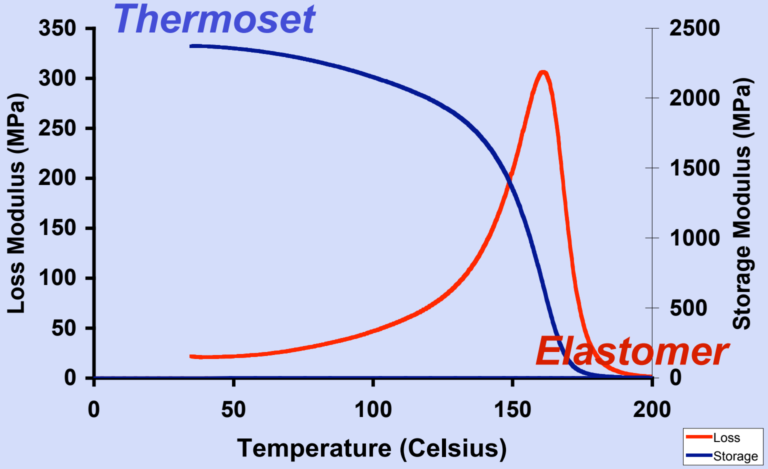
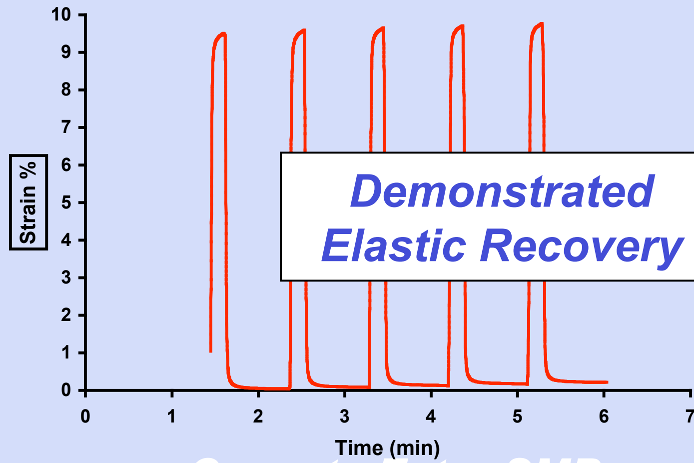
SMP Development - Cyanate Ester

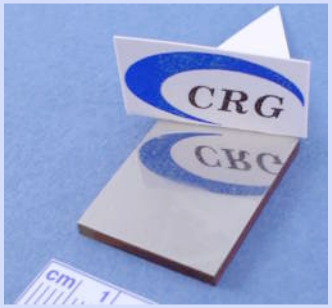
- **CE polymers already used in space**
- **Transformed conventional CE to SMP**
  - Fully cured, cross-linked for stability
  - Required new polymer design
- **CE shape memory polymer results:**
  - Deformation-recovery cycle demonstrated
  - Activation temperature of 160°C
- **Optimization**
  - Enhanced strain recovery
  - Increased toughness

Cyanate Ester SMP Modulus





Cyanate Ester SMP



Coated CE SMP

Carbon Nanofiber-CE SMP Composite Membrane (0.5.kg/m²)

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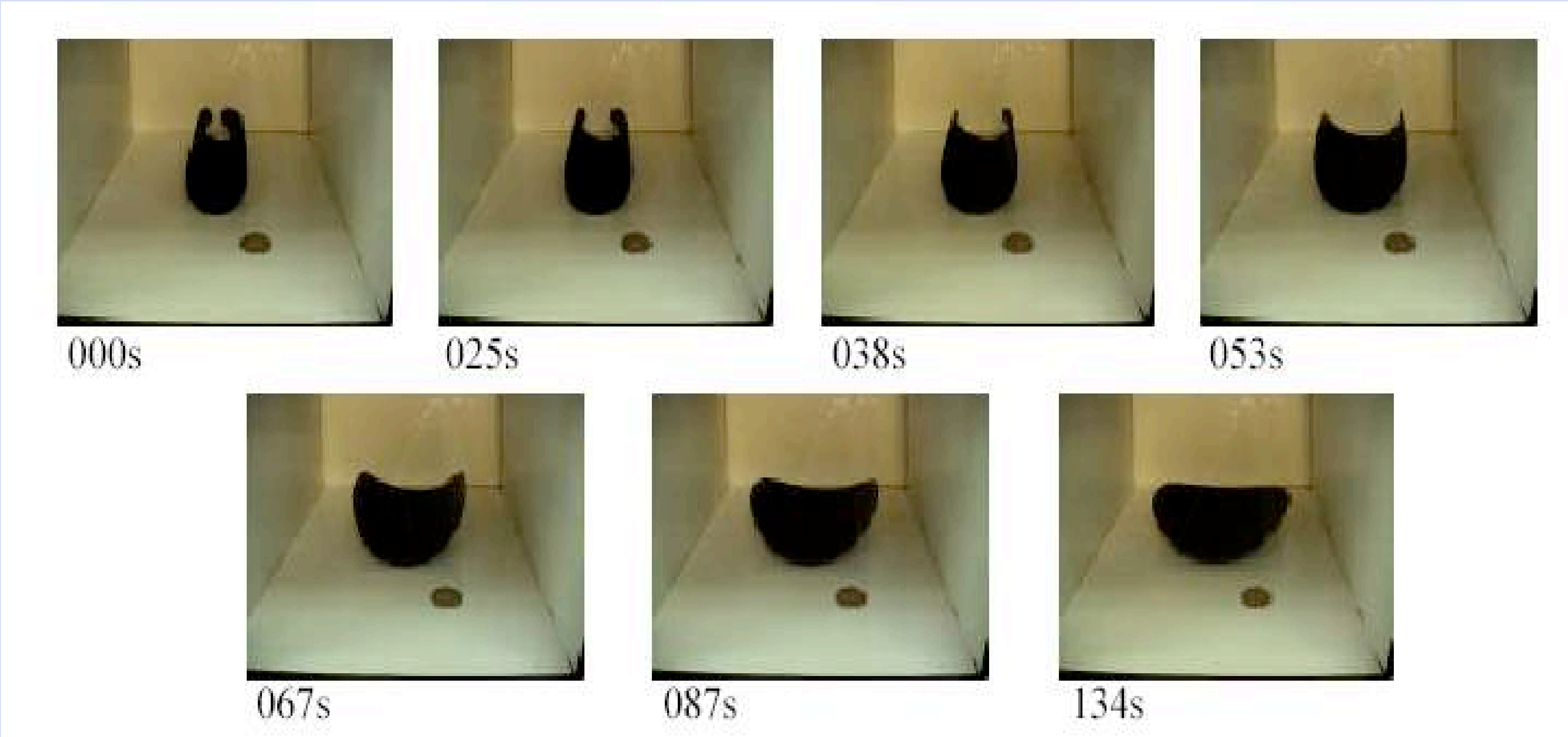
Deployment test of spherical surface -no damage to structure

- **Self-Deployment tested in oven at 110C**
- **Lower temp activation polymer being developed**



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Initial Deployment Test Results Mixed

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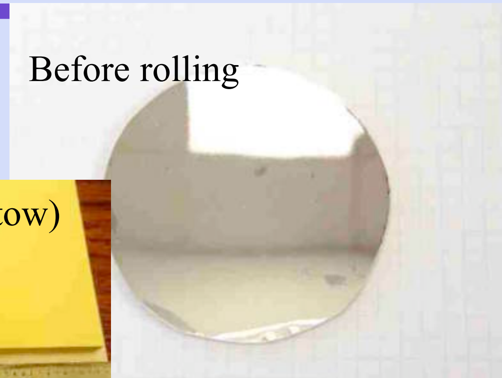
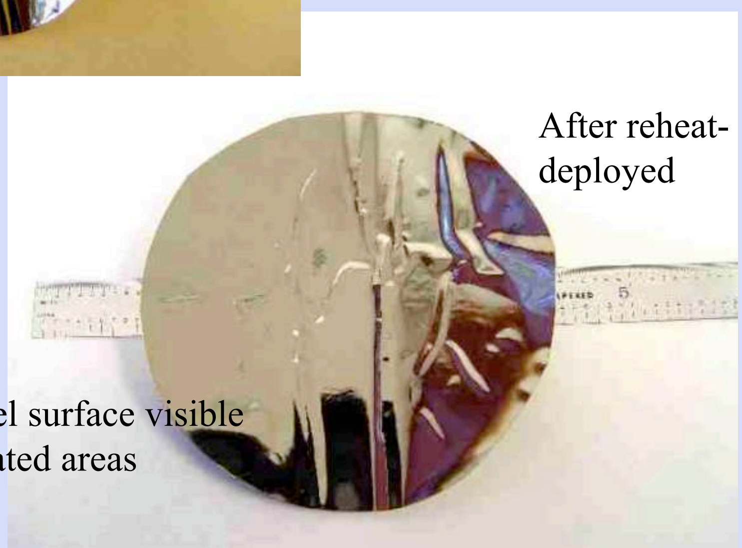


Before rolling

Rolled to 15mm radius (stow)

Delamination occurred during heating, not during rolling



After reheat-deployed

Damage to nickel surface visible only in delaminated areas

- **First Deployment Test**
  - Optical figure after release from mandrel was poor- astigmatic
  - Temperature cycling – shape was unchanged by heating, some additional delamination
  - Deployability concept validated– Areas without delamination did not show nickel surface damage when stowed at a 15 mm radius (100x tighter than a flight item) and then redeployed to near-original shape
  - Nickel-composite adhesion will be researched further - several options available

Deployed Mirror surface undamaged by deployment

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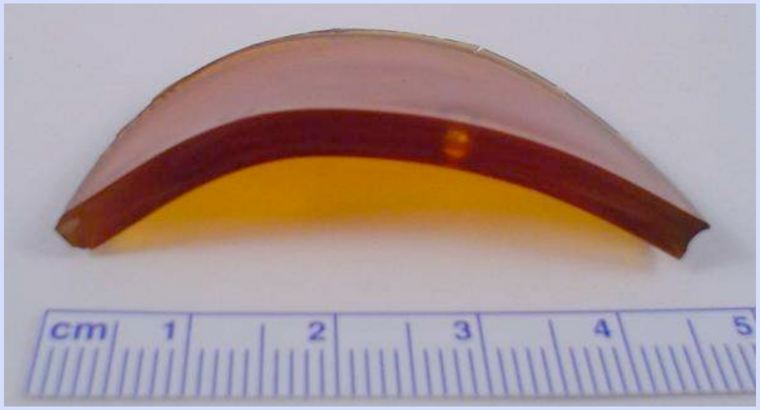
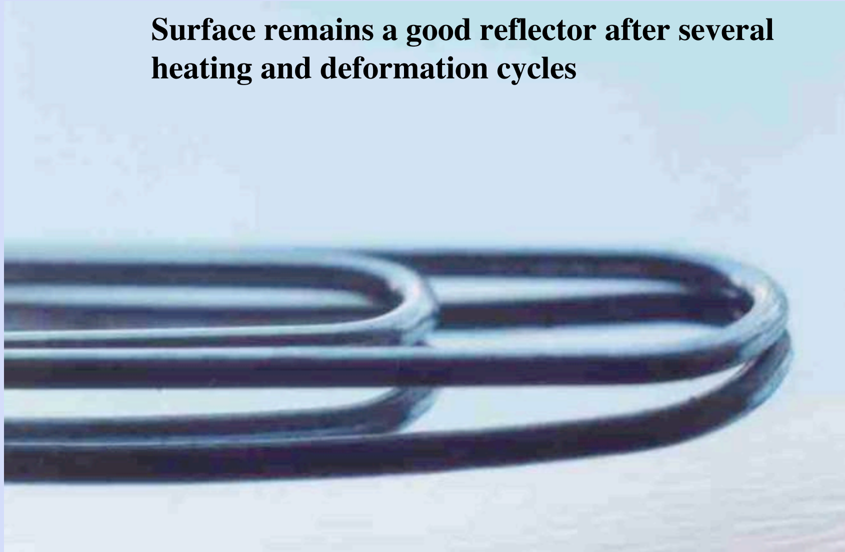


- Buckling was observed <u>but only where delaminated</u>
- Remains smooth after several heat annealing cycles
- Surface is smooth at resin cure temp (CTE mismatch)



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Ion etched rear surface of nickel greatly improves adhesion

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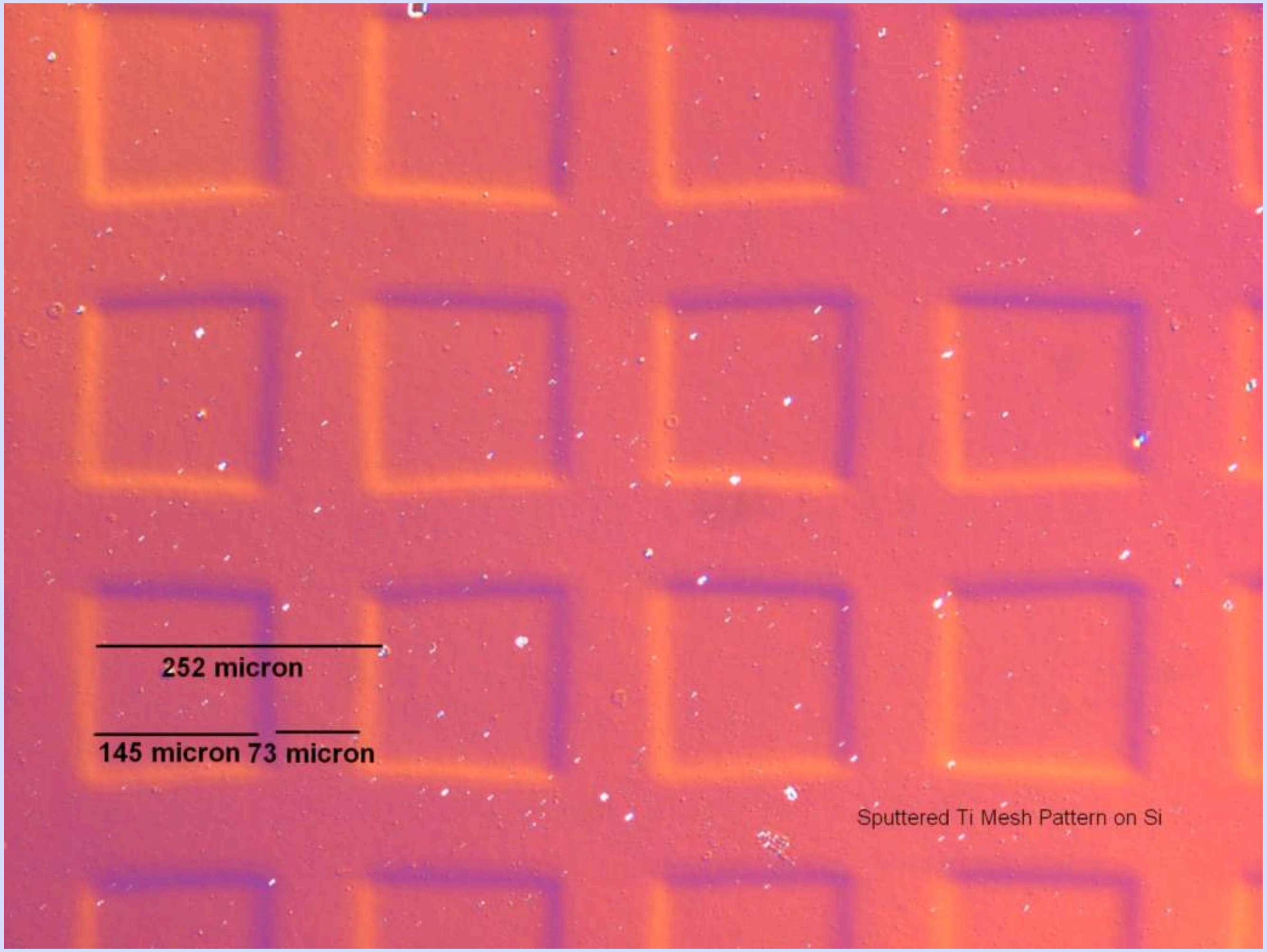
No Delamination

Thermal cycled 0-200C

Deformed to 20 mm radius



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Print through remains a challenge, but is significantly reduced

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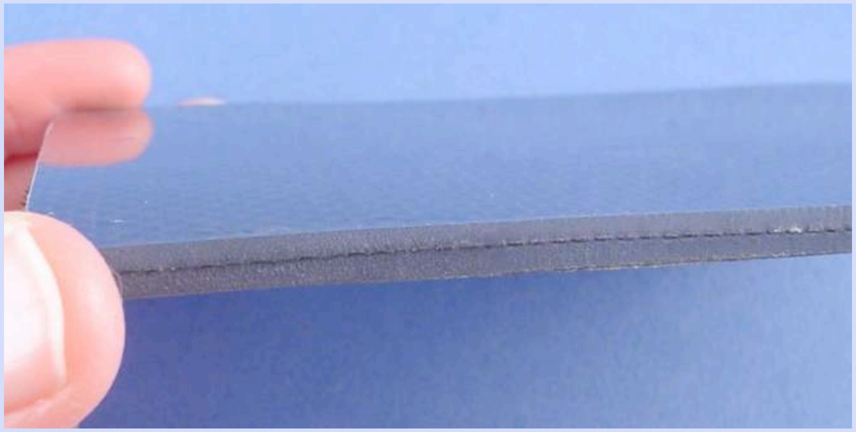
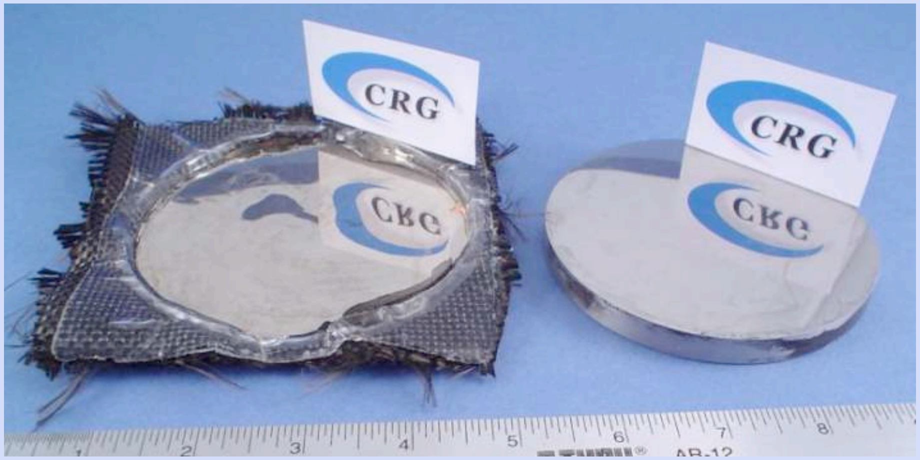


- Fiber-resin CTE mismatch produces print through
- Sandwich approach is improvement, without fibers near surface
- Neat (resin rich) layer surrounds fiber reinforcement
- Nanofibers and alternate filler reinforcement being investigated



- Neat resin layer reduces fiber print-through effect, but nickel-thermal mismatch caused waviness

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MultiLayer Lamination reduced moisture loss 40%

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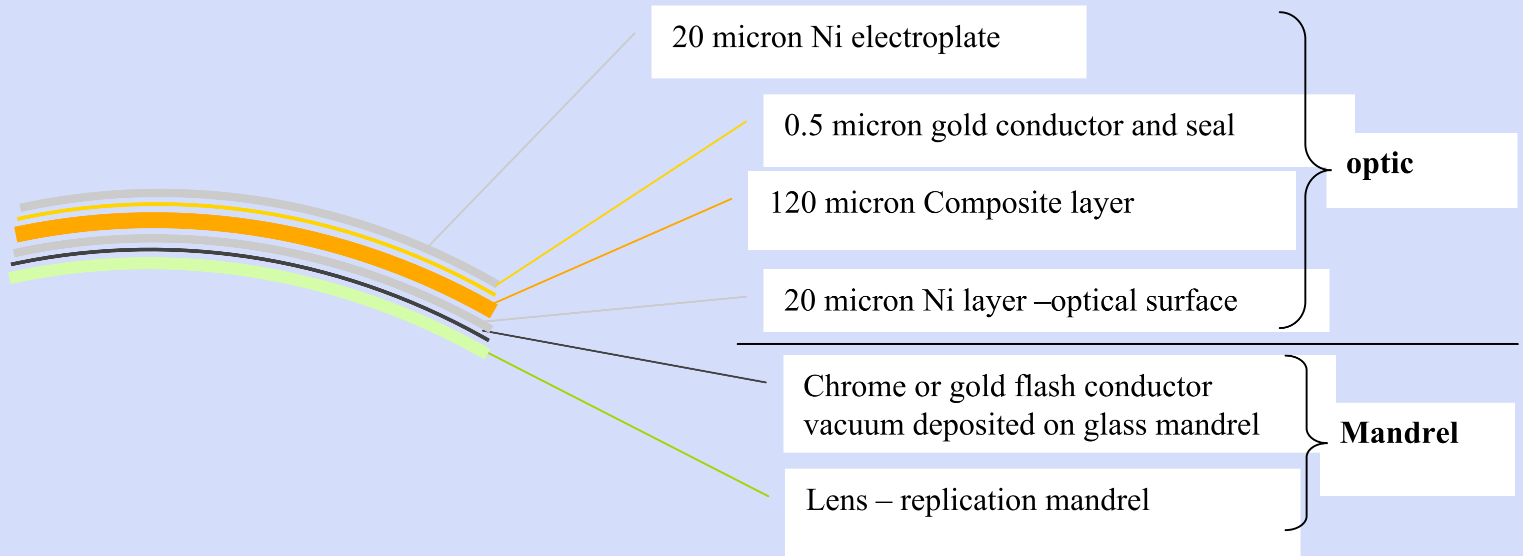

- **Nickel on both optical surface and rear surface equalizes thermal stresses and seals composite from moisture absorption/loss and outgassing creep**
- **Thermal vacuum tests show 40% lower moisture loss. Stress relief and dimensional stability TBD**
- **Optical testing -figure and surface roughness poor on this sample due to abandoned structure concept. Test to be repeated on a better test item utilizing new adhesion process and structure for print through reduction.**
- **Deployment test –Determine if it can be rolled and unrolled without permanent damage with delamination and creasing.**

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Shape Memory Mirror Feasibility Demonstrated

- Figure: Low stress nickel process produces <10 waves PTP mirror. Composite replication needs development
- Roughness: Low scatter nickel achieved 2nm RMS
- Outgassing: Shape Memory CE resin meets requirements (0.16% TML)
- Spherical Surfaces: Reinforced composite SMP applied to flat and spherical nickel plating surfaces
- Adhesion: Demonstrated ruggedness of nickel-composite lamination
- Stow and deployment demonstrated without damage to optical surface, deployment repeatability needs development

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Critical parameters for continued investigation

- **Modeling –Validate prediction of symmetric layers and measured composite properties. Stress model to include matrix of position elements to translate to surface figure and optical performance. Validate scaling laws.**
- **Flat mirror production fabricate test items for structural data and model verification, and surface finish/print through**
- **Spherical mirror production –compare performance of improved adhesion, and reduced print through, improved surface figure, figure adjustment**
- **Deployability: cycling without damage or change, repeatability**
- **Stability and creep: improvement on conventional composites**
- **Polymer development:**
  - low CTE resin/composite
  - low cure temp minimizes
  - Reinforcement of resin for CTE match, low print through structure
- **Optimize nickel thickness to match composite properties**

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Near Term Goals

- **Scale up- to 30-40 cm**
  - Complete analytical modeling of components and lamination and fold into the integrated model for optical predictions
  - Validate analytical model and extend to spherical surfaces
  - Demonstrate optical surface replication and stability
  - Demonstrate repeatability of deployment (overcome residual strain)
- **Develop structural concepts for accurate deployment**
- **Validate key processes and performance, and the connection between them**
  - Low temp cure and deployment,
  - Reverse side plating for stability
  - Evaluate low CTE resin/composite and room temp cure

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Conclusions

- **Laminated nickel – composite optics can provide deployable optical surfaces without delamination or deterioration of metal surface and substrate**
- **Shape memory control provides more design latitude for deployable optics**
- **Typical deployment accuracy is consistent with needs for microwave reflectors of 1-2 meter diameter**
- **Additional work needs to be done**
  - Resin chemistry (low CTE, low temp cure,)
  - Structures (optimizing deployment, modeling in stow condition)
  - Durability in the space environment